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Evaluation of Mechanical and Tribological Properties of Glass/Carbon Fiber Reinforced Polymer Hybrid Composite

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ABSTRACT

Polymer matrix composites used in different industrial applications due to their enhanced mechanical properties and lightweight. However, these materials are subjected to friction and wear situations in some industrial and automobile applications. Therefore, there is a need to investigate the wear properties of polymer matrix composite materials. This article emphasizes the dry abrasive wear behavior of a hybrid glass/carbon ($[GCGGC]_S$) composite. The mechanical and wear properties of the composite was evaluated and compared with maiden glass and carbon fiber reinforced polymer composite. Design of experiment of Box-Behnken type was adopted to perform the experiments. Response surface methodology (RSM) was employed to optimize the experimental parameters to minimize the specific wear rate of the composites. A second order mathematical model was developed. The model has predicted the optimum input parameters for minimum specific wear rate of 18.847×10^{-3} mm^3/Nm for the hybrid ($[GCGGC]_S$) composite. Furthermore, the model predicted specific wear rate value was validated with experimental one and found a close agreement between them.

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1. INTRODUCTION

Polymer matrix composites have wide potential applications in aerospace and automobile industries [1]. Glass/carbon fiber reinforced polymer composites (GRPC) have been used in automotive application due to its high specific strength [2]. However, further improvement of strength is necessary for structural applications. Nayak et al. [3, 4] have reported that one of the improved methods is addition of nano-Al_2O_3 particles into the epoxy matrix can enhance the flexural and interlaminar shear strength of the nano-composites. Carbon fiber reinforced polymer composite (CRPC) has been used in automotive application due to their light weight, superior strength and stiffness. However, it has low elongation and shows catastrophic failure in service [5]. Heydari et al. [6] studied the strain energy release rate for mode-I and mode-II loadings. The fracture surface showed brittle failure with less debonding in mode-I and broken fibers with rough surface in mode-II failure. Khemedi et al. [7] attempted to locate defect and failure by non-destructive method of carbon/epoxy composites and evaluated failure mechanisms by acoustic emissive waves. The catastrophic failure of carbon fiber reinforced composite can be avoided by the addition of fibers having moderate modulus and better strain like E-glass fiber. The high modulus carbon fiber will bear the major load, whereas low modulus fiber like E-glass fibers will enhance the toughness [8]. Furthermore, the mechanical properties of the resulting composite are dependent on volume fraction and stacking sequence of different fiber layers [9]. Zhang et al. [2] investigated the effect of stacking arrangement on mechanical properties of hybrid glass/carbon epoxy composites. They have reported that for 50% carbon fiber reinforcement and carbon layers on the exterior resulted in better flexural properties. Giancaspro *et al.* [10] reported that the flexural strength of glass fibre polymer composites can be enhanced by incorporating carbon fiber at the tensile region. Khalkhali et al. [11] designed automobile drive shaft by multi-objective optimization of hybrid carbon/glass fiber reinforced

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epoxy composite. They found that for the same load capacity, the composite drive shaft has higher natural frequency and reduced weight compared to the steel drive shaft. Srinivas and Bhagyashekar [12] observed that hybrid particulate of higher fraction of graphite and lower fraction of SiC has high abrasion resistance. Sudheer et al. [13] have found that epoxy/glass composites with PTW/graphite hybrid fillers enhances the mechanical and wear properties by inclusion of graphite as filler. Mohan et al. [14] studied the wear properties of hard powders filled glass fabric–epoxy hybrid composites. Suresha and Chandramohan [15] has found that 3-D glass fabric reinforced vinylester improves wear resistance with silicon carbide filler compared to graphite filled composites. Visconti et al. [16] performed the three body abrasion test in glass-epoxy composites with silica (SiO_2) and tungsten carbide (WC) as fillers. They have found that the tungsten carbide filled glass-epoxy composites shows lower specific wear rate. El-Tayeb et al. [17] developed an empirical model for wear using RSM for optimization of sliding distance, applied load and sliding time on dry abrasion properties of titanium alloys. Siddhartha and Gupta [18] observed that chopped glass fiber reinforced composites performed better than bi-directional glass fiber reinforced composites under abrasive wear conditions. Suresha et al. [19] found that carbon-epoxy composites shows better abrasion wear resistance compared to glass-epoxy composites. Yousif [20] reported that glass fiber reinforced polyester composites exhibited better frictional and wear performance when the glass mat was parallel to the sliding direction compared to the perpendicular one. Tunalioglu et al. [21] investigated wear in internal gears with polymeric coating such as PTFE, MoS2 in polyamide and MoS2 in epoxy. They have observed high wear resistance due to lower frictional coefficient and better lubrication compared to uncoated ones.

The effect of fiber sequence on tribological properties has not been evaluated and reported in open literature enormously. Therefore, in this article, ten layered of maiden glass and carbon reinforced composite along with a hybrid composite having symmetric stacking sequence of $[GCGGC]_S$ fabricated by hand lay-up technique. The hardness, tensile, flexural and wear properties of the composites were determined and compared with maiden composites. Box-Behnken Design of experiment is used to reduce the number of experiments to be condcted. A polynomial mathematical model has been developed using response surface methodology.

2. EXPERIMENTAL WORK

2. 1. Material Carbon fiber of 200 gsm, a 2×2 twill woven roving of density 1.76 g/cm3 procured from Soller Composites. The glass fiber of 360 gsm, plain woven E-Glass of density 2.52 g/cm3 was procured from Owens Corning, India. Composites were fabricated using epoxy having density 1.16 g/cm3 (Diglycidyl ether of Bisphenol A) marketed as Lapox L-12 and hardener (Triethylene tetraamine) marketed as K-6 procured from Atul Industries, India. The fiber and polymer mechanical properties reported in Table1.

2. 2. Fabrication of Composite Laminates The composites were fabricated by reinforcement of glass and carbon fibers in the epoxy polymer matrix by hand lay-up method. The ratio of epoxy to hardener was 10:1. The hybrid composite consists of ten layers of which six layers were glass fibers and four layers of carbon fibers ($[GCGGC]_S$). The composites were kept under a load of 10 kg for 24h at room temperature for initial curing. Specimens were cut to dimensions as per test specifications and then post-cured in an oven at 140 ^{O}C for 6 hours before testing [23, 24].

3. RESULTS AND DISCUSSIONS

3. 1. Flexural Strength Flexural strength and modulus were measured according to ASTM D7264 standard. The rectangular specimen dimensions are 70 mm (length) × 13 mm (width) × 3 mm (thickness). The flexural test was carried out using Instron 5967 Universal Testing Machine (UTM) at room temperature shown in Figure 1. The span length of 60 mm and the crosshead speed of 2 mm/min has considered during the test. Three specimens were tested, and their average values are reported.

TABLE 1. Materials properties [22]

Property	Glass fiber	Carbon fiber	Epoxy
Tensile Stiffness (GPa)	76	230	3.6
Tensile Strength (MPa)	3100	3530	70
Strain to failure (%)	4.5	1.5	4.6

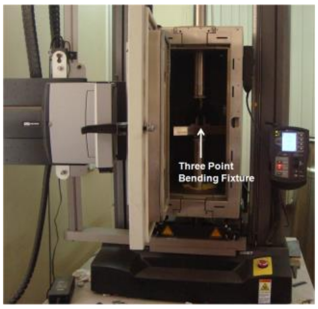

Figure 1. Three-point bending fixtures in Universal Testing Machine (Instron)

Figure 2 shows the flexural strength, modulus, and extension of the composites. The results revealed that the GRPC has the lowest flexural strength and highest flexural extension, whereas CRPC has the moderate flexural strength and lower extension. The flexural strength of $[GCGGC]_S$ is 461.8 MPa which is marginally more than plain carbon composites. That may be due to intermediate bridging action of glass fibers in intermediate layers of the hybrid composite. Hybrid composite of $[GCGGC]_S$ has higher flexural modulus and increased by 45% as compared to GRPC. It may be because of higher stiffness of intermediate carbon layers. Similarly, the flexural extension of $[GCGGC]_S$ hybrid composite is 45% more than CRPC. It may be due to the higher ductility of outer glass fiber layers.

3. 2. Hardness The hardness of the composites was evaluated as per the ASTM D2583 standard using Barcol hardness tester of Barber Colman, USA version GYZJ-934-1. Three specimens were tested, and their average values are reported. Figure 3 shows the hardness of glass, carbon and hybrid composites.

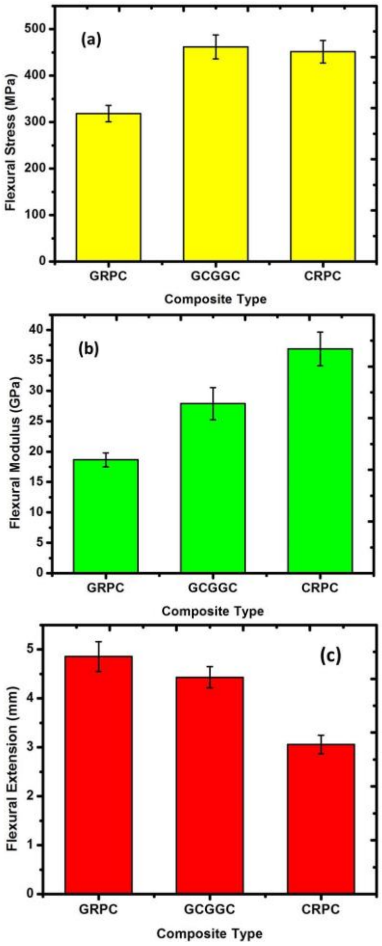

Figure 2. (a) flexural strength, (b) flexural modulus and (b) flexural extension of composites

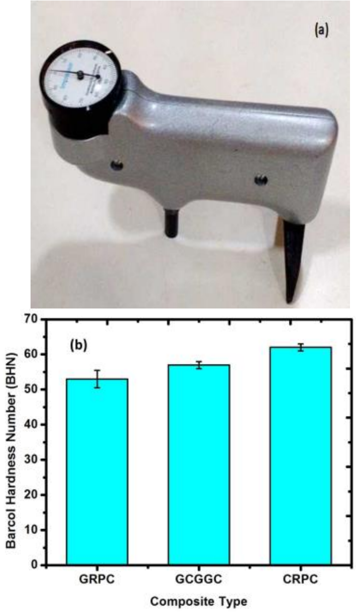

Figure 3. Barcol Hardness tester (a) and hardness of the composites (b)

The hardness of CRPC is 62 BHN, and GRPC is 53 BHN. However, the hardness of $[GCGGC]_S$ is 57 BHN, which is more than GRPC. It may be due to the presence of carbon fiber in the intermediate layers of $[GCGGC]_S$.

3. 3. Surface Reseponse Methodology In this investigation, modeling and optimization of input parameters such as composite hardness (H), sliding distance (D) and applied load (L) have been performed using Box-Behnken Design of Experiment (DOE) of Response Surface Methodology (RSM) to minimize Specific Wear Rate (SWR). Minitab 17 is a statistical software, which is used to create and analyze the design matrix. In this investigation, each factor had three levels and reported in Table 2.

3. 4. Abrasive Wear Test The three-body abrasion wear test was performed as per ASTM G65 standard using DUCOM TR-50 abrasion tester. The abrasion tester contains a steel wheel covered with chlorobutyl rubber on its outer layer. The sample holder holds the rectangle sample of size 76 mm (length), 25.4 mm (width) and 3 mm (thickness).

TABLE 2. Factors and their levels in Box-Behnken Design of experiment

Input parameters	Symbol	Levels		
		Low	Middle	High
Composite Hardness	H	53	57	62
Sliding Distance	D	420	840	1260
Applied Load	L	12.75	25.5	38.26

It is designed in such a way that the sample to be tested is pressed against the rotating rubber wheel. The dry abrasion tests were carried out at a fixed rotational speed of rubber wheel i.e. at 125 rpm. Silica sand of grit size 60 micron is used as the abrasive medium and it is fed between the contact surfaces of the rubber wheel and the sample. Figure 4 shows the dry abrasion experimental setup.

Fifteen randomly chosen experiments have been performed as per Box-Behnken DOE. The specific wear rate (SWR) of different composites has been calculated using Equation (1).

$$SWR = \frac{\Delta V}{Load(L) \times Distance(D)} \tag{1}$$

where, ΔV is the volume loss (mm^3), L is the applied load (N) and D is the sliding distance (m).

3. 5. Model Development and its Optimization

The wear property of the composite depends on both material properties as well as operating conditions. Table 3 represents 15 numbers of experiments according to Box–Behnken design of the experiment and the corresponding experimental specific wear rates (SWR) results. Analysis of Variance (ANOVA) is a statistical method which draws a set of conclusion based on experimental data. The ANOVA results of SWR are reported in Table 4. From ANOVA results, it is observed that R-square is 99.47% and it means the model is valid and close agreement with the experimental data.

The high value of R^2 adj (98.52%) and R^2 pred (92.24%) indicate that the model has very good predictability. The quadratic model for specific wear rate is developed by response surface methodology is expressed in Equation (2).

$$\begin{aligned} SWR &= 364.9 - 11.44H - 0.0183D - 0.569L + \\ &0.113H^2 + 0.00000D^2 + 0.03941L^2 - \\ &0.000182H \times D - 0.03675H \times L + 0.000163D \times L \end{aligned} \tag{2}$$

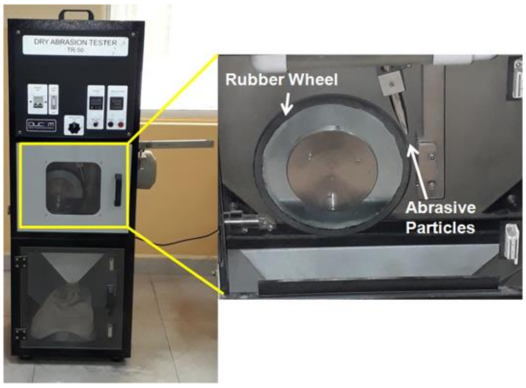

Figure 4. DUCOM TR-50 dry abrasion tester

TABLE 3. Experimental design and results of Abrasive wear of composites

Exp. Run	Independent Variables			Response
	Composite Hardness (BHN)	**Sliding Distance (m)**	**Applied Load (N)**	**Specific Wear Rate (×10^{-3} mm^3/Nm)**
	(H)	**(D)**	**(L)**	**(SWR)**
1	57	840	25.50	23.9773
2	57	840	25.50	23.4500
3	57	1260	12.75	31.4840
4	62	1260	25.50	22.2864
5	62	420	25.50	36.0043
6	53	840	38.26	25.1637
7	57	1260	38.26	19.5439
8	57	420	38.26	28.6990
9	62	840	38.26	26.5872
10	53	1260	25.50	18.7646
11	62	840	12.75	43.9762
12	57	420	12.75	44.1293
13	53	840	12.75	34.0000
14	53	420	25.50	31.3479
15	57	840	25.50	23.0000

TABLE 4. ANOVA results for SWR

Source	DF	Adj SS	Adj MS	F-value	P-value
Model	9	885.690	98.410	104.69	0.000
Linear	3	15.457	5.152	5.48	0.049
H	1	14.321	14.321	15.24	0.011
D	1	1.297	1.297	1.38	0.293
L	1	1.153	1.153	1.23	0.318
Square	3	164.320	54.773	58.27	0.000
H*H	1	18.993	18.993	20.21	0.006
D*D	1	4.296	4.296	4.57	0.086
L*L	1	151.817	151.817	161.51	0.000
2-way interaction	3	21.426	7.142	7.60	0.026
H*D	1	0.476	0.476	0.51	0.508
H*L	1	17.903	17.903	19.05	0.007
D*L	1	3.047	3.047	3.24	0.132
Error	5	4.700	0.940		
Lack-of-Fit	3	4.221	1.407	5.88	0.149
Pure Error	2	0.479	0.239		
Total	14	890.390			

R^2= 99.47%, R^2 (adj) = 98.52%, R^2 (pred) = 92.24%

Figure 5 shows the normal probability plot for SWR, where the residuals are close to the straight line. It means the experimental data is normally distributed and reliable.

3. 6. Effect of Independent Variables on Specific Wear rate

Three-dimensional (3D) surface plot for the specific wear rate (SWR) model according to Equation (2) is plotted in Figure 6. Figure 6(a) shows the 3D surface plot against H and L for specific wear rate where for low values of composite hardness and high values of applied load, specific wear rate decreases. The results revealed that SWR of the composites decreases as the applied load increases. This may be due to accumulation of wear debris between the abrasive asperities that had broken off from the softer materials. Figure 6(b) shows the 3D surface plot of SWR against D and L. The results revealed that with high value of sliding distance and low value of applied load, there is drastic reduction in specific wear rate. Figure 6(c) shows the 3D surface plot of SWR against D and H, it is seen that specific wear rate decreases with the increase of sliding distance and decrease in hardness of the composites.

3. 7. Predictions of Optimum SWR

Figure 7 depicts the desirability plot for specific wear rate of the composites. The predicted optimum conditions to achieve minimum SWR for the hybrid ($[GCGGC]_S$) composite is sliding distance of 1100m and applied load of 33.15 N with desirability of 0.9967. The RSM model predicts the optimum independent variables, their levels and corresponding response (SWR) for hybrid ($[GCGGC]_S$) composite. The confirmation test was experimentally carried out to verify the repeatability and reproducibility of the model results. The SWR obtained from the confirmation experiment has close agreement to the predicted data obtained in desirability optimization by RSM.

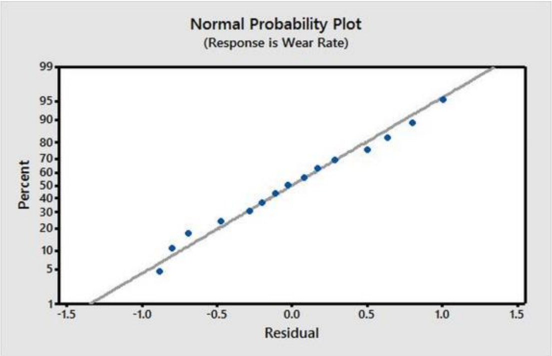

Figure 5. Normal Probability Plot of residuals for SWR

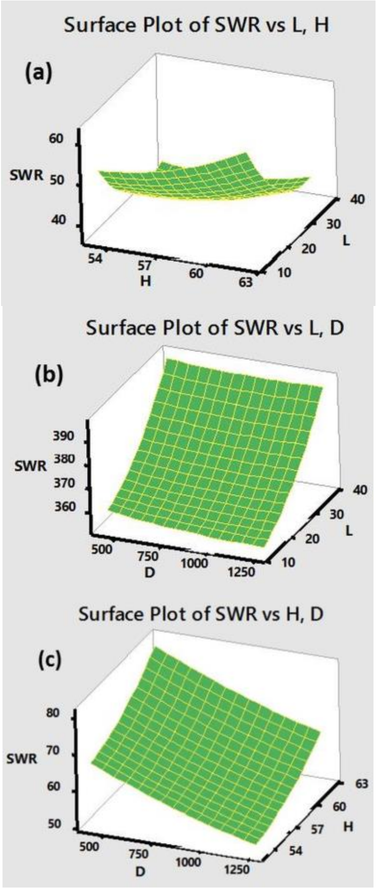

Figure 6. 3-D surface plot of (a) SWR versus L and H (b) SWR versus L and D and (c) SWR versus H and D

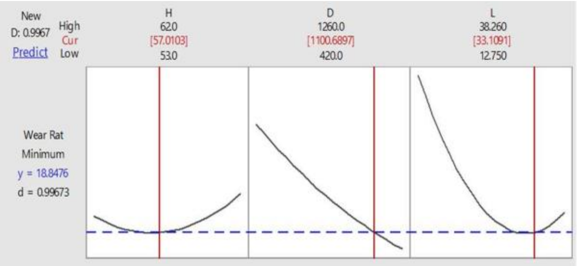

Figure 7. Desirability Plot for response optimization

TABLE 5. Comparison of optimal parameters

Optimal Parameters	
Prediction	Confirmation test results
Composite Hardness-57BHN	Composite Hardness-57BHN
Sliding distance-1100m	Sliding distance-1100m
Applied load -33.15N	Applied load -33.15N
SWR =18.8476×10^{-3} mm3/Nm	SWR =18.7452×10^{-3} mm3/Nm

4. CONCLUSION

Maiden and hybrid composite of glass and carbon fiber reinforced polymer composite $[GCGGC]_S$ has been fabricated by hand lay-up method successfully. The mechanical and specific wear rate of the hybrid composite were evaluated and compared with maiden composites. The results revealed that the flexural strength, flexural modulus of $[GCGGC]_S$ is increased by 45 and 50%, respectively than that of GRPC. The flexural extension of $[GCGGC]_S$ is improved by 45% as compared to CRPC. Furthermore, a second order mathematical model was developed to determine the specific wear rate by Box-Behnken design of experiment (DOE) of response surface methodology. From ANOVA, it is observed that all three independent variables; i.e. composite hardness, sliding distance and applied load are contributing for the prediction of specific wear rate. The model predicted input parameters for minimum specific wear rate of 18.8476×10^{-3} mm^3/Nm are sliding distance of 1100m and applied load of 33.15 N. The model predicted result has confirmed with experimental one and found a good agreement between them.

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چکیده

کامپوزیت ماتریس پلیمری به دلیل ویژگی خاص در کاربردهای مختلف صنعتی های مکانیکی و سبک وزن آنها افزایش یافته است. با این حال، این مواد در برخی از برنامه های صنعتی و خودرو اصطکاک مورد استفاده هستند. بنابراین نیاز به بررسی خواص پوششی مواد کامپوزیتی ماتریکس پلیمری است. این مقاله تاکید بر رفتار سایش خشک ساینده یک ترکیب شیشه ای / کربن هیبریدی ([GCGGC] S) است. خواص مکانیکی و پوششی کامپوزیت با کامپوزیت پلیمرهای تقویت شده فیبر کربن شیشه و شیشه ای مورد مقایسه قرار گرفت. طراحی آزمایشی نوع Box-Behnken برای انجام آزمایشات انجام شد. به منظور بهینه سازی پارامترهای آزمایشی برای به حداقل رساندن سرعت سایش ویژه کامپوزیت ها، روش پاسخ سطح (RSM) مورد استفاده قرار گرفت. یک مدل ریاضی مرتبه دوم توسعه یافت. این مدل پارامترهای ورودی بهینه را برای کمترین سرعت سایش ویژه 18.847×10^{-3} mm^3/Nm برای ترکیبی ([GCGGC]s)) کامپوزیت پیش بینی شده است. علاوه بر این، مدل پیش بینی شدهٔ میزان سایش ویژه با استفاده از آزمون تجربی یکسان بود و توافق نزدیک میان آنها موجود بود.

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